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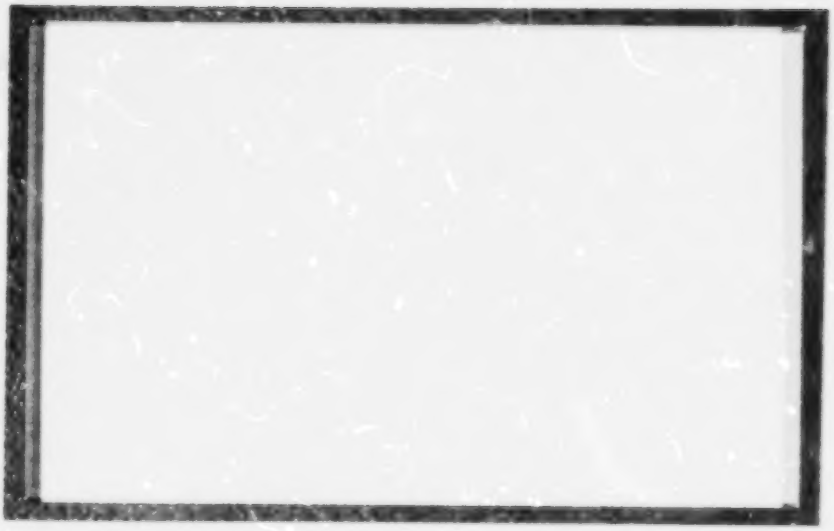

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SUPPLY MODELS FOR INTERCITY PASSENGER TRANSPORTATION : A REVIEW

by

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ABSTRACT

This paper presents a review of supply models in the field of intercity passenger transportation, together with an attempt to characterize these models with regard to normative and predictive approaches, and in relation to the full hierarchy of strategic, tactical and operational decision-making situations. Part of the paper also deals with computerized decision support systems. Major research directions are presented and the main opportunities for further research are identified.

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1. INTRODUCTION

The intercity passenger transportation industry plays a major economic and social role, at regional, national and international levels. This industry, now more than ever, is crucial to a variety of professional, commercial, industrial and social activities which require individuals to travel.

As with many other sectors however, this industry has suffered in recent years from a difficult economic situation, and several companies are now facing severe problems. Various changes have occurred : there is now increased competition between transportation modes and companies; there have been significant shifts in cost structures, in particular with regard to energy and labor costs; the rate of growth of demand has decreased, at least for certain modes, and higher interest rates have resulted in higher capital costs, etc. The current tendency towards major deregulation in Canada will give increased freedom of action to all transportation companies, but one may expect that it will result in further competition and a more difficult task for planners and managers confronted with severe financial constraints.

Transportation planners and managers, including those at the government level responsible for the supply of certain major transportation services and facilities, are thus facing a complex and changing environment, while being forced to provide more and better services at lower costs. In addition, decisions must be made at various different levels, from medium and long term planning to short term operational procedures, and all decisions have multiple direct and indirect impacts which interact with each other. In such a context, the definition and economic evaluation of decisions become a real challenge : more than ever, planners and managers must design new services and facilities very carefully, and examine

existing ones very critically, in order to be efficient and competitive while financially healthy.

Unfortunately, decision-makers concerned with intercity passenger transportation possess few tools with which to grasp the multiple effects of all their possible decisions. Research in this field of transportation has been mainly concentrated on the development and calibration of demand models to simulate and predict transportation demands, aggregated by mode in the best cases, between pairs of cities. Important methodological advances concerning these models have occurred in recent years (see for instance Stopher and Meyburg, 1976; Gaudry and Wills, 1978; Rice et al., 1981; Lerman, 1984; Gaudry, 1984). However, these models are not very helpful to companies when the time comes to decide in detail about effective levels of service and fares, to plan vehicle schedules and flows on large and complex networks, to choose new service lines or cancel existing ones, to purchase or lease vehicles, to evaluate possible stategies of competing modes or companies in a sensitive market place, to adapt to variations in the price of oil, etc. Neither do they provide policy-relevant information to government bodies when, in a context of deregulation, the supply of transportation services and the utilization of the transport infrastructure may change drastically. In other words, for effective decision-making with regard to planning and management of transportation services, facilities and controls, there is a need for other theoretical and methodological approaches concerned mainly with supply actions and policies.

In recent years, fortunately, such interest in the study of the supply side of transportation has greatly increased. Much of the early work was in the area of urban transportation, but recently intercity transportation has received more attention. The changes mentioned above undoubtedly lie at the root of this development in research.

This paper deals with supply models for the vast domain of intercity passenger transportation. It is organized as follows. Sections 2 and 3 present the concept of transportation supply, together with an attempt to characterize supply modelling activity in terms of predictive and normative approaches, as well as in relation to the full hierarchy of strategic, tactical and operational decision-making situations. Section 4 reviews the state of the art and promising research opportunities are identified in the field of predictive supply models. Section 5 does the same for normative supply models. Section 6 deals with a somewhat different but related area of research which concerns computerized decision support systems. In section 7, we discuss the important issue of data requirements, while section 8 concludes the paper with some general comments.

2. THE CONCEPT AND MODELLING OF TRANSPORTATION SUPPLY

Like Manheim (1980) and Florian and Gaudry (1980, 1981), we view a transportation system as the collection of all physical, social, economic and institutional components which relate to the transportation of people (or goods in the case of freight transportation) in a given, well specified context. Also, we recognize the existence of both demand and supply sides of transportation systems.

As emphasized in our introduction, models dealing with the demand side of transportation have been marked by significant methodological advances. These models predict the number of trips demanded or the market share of a mode, provided that relevant explanatory variables, including levels of service and fares, are known (Florian and Gaudry, 1980), i.e. when all technological and operating characteristics of the supply are fixed.

On the other hand, the study of transportation supply involves both the technology of providing services, and the management activities of

suppliers (Turnquist, 1985); it involves all possible changes and more generally all possible supply actions concerning technologies, networks, links, infrastructures, vehicles, organizational policies, operations, etc.

Supply models generally address explicitly one of the two following questions :

- What will happen if one implements a given supply action?
- What supply action should be undertaken in order to optimize a given objective?

In other words, these models deal explicitly with the evaluation or with the "optimal" determination of supply actions, including the complete spectrum of technological, policy, operational, regulatory... decisions. Both predictive models on the one hand ("what will happen if ...") and normative models on the other hand ("what should be done in order to ...") are concerned with understanding how to intervene effectively in large, complex, transportation systems.

Predictive supply models are concerned with the prediction of the impacts of proposed supply actions on the performance of transportation systems. Their main utility stems from the fact that they offer the possibility of considering different alternative exogenous supply actions over a given range and to evaluate each of them for the purposes of comparison. The importance of the concept of performance within this category of supply models leads some authors to refer to them as "performance models", since one of their main capabilities is to relate level-of-service measures to demand levels and specific technological supply options e.g. vehicle types, guideway characteristics, schedules, operating rules, traffic control, etc. (Turnquist, 1985).

From our point of view, the above-mentioned interpretation of performance is however too restrictive. Like Manheim, we believe that at

least two major aspects of transportation system performance are important. The first aspect has been defined above, i.e. the one which deals with the representation of service levels as a function of demand levels and supply actions. The second performance dimension is that which describes the resources consumed by the transportation system as a function of the same variables, i.e. demand levels and supply actions. In practice, it is sometimes convenient to deal with just one of these two performance dimensions, but the fact remains that they are closely interrelated. To summarize, the concept of performance is central in predictive supply models as defined above : it reflects a user perspective and/or an operator perspective, the former being interested in service levels and quality, and the latter being interested (among other things) in resource consumption costs required to provide services. Note that the evaluation of the performance of a transportation system should also include the examination of external impacts on other social groups, for instance through air pollution or through taxes for distribution of resource costs.

In addition, it should be emphasized that the concept of performance applied to the representation of service levels is more useful if such a performance measure is interfaced with a demand model or, better still, with a passenger assignment model of some sort in order to predict how supply actions influence the behavior of travellers. In other words, a performance function or procedure[1] is usually embedded in a larger modelling effort which addresses the equilibrium of transportation supply and demand. This is the reason why we prefer to speak of "predictive supply models" rather than "performance models", which is a more restrictive term in our opinion. To summarize, the objective of predictive supply models is the evaluation of supply actions with the explicit prediction of impacts on

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[1] Such a procedure may consist of one or more functions, models, algorithms, etc.

users and/or suppliers of transportation services, and these models usually include performance functions interfaced with demand functions. For instance, a model to determine the cost of a flight schedule proposed by an airline and the distribution of passengers amongst flights would be a predictive supply model.

Normative supply models, which represent the second category of models dealt with in this paper, involve an endogenous treatment of supply actions : they are concerned with the exploration of the space of all possible actions to find the supply actions plan which is most attractive with regard to certain objectives or decison rules. These normative models are devoted to the design of networks, of services, of vehicle routes or schedules, etc., as well as to the solution of other related design problems such as vehicle fleet sizing, terminal capacity planning, etc. Since the actions of suppliers of transportation services and facilities are based on the estimation or prediction of the performance of such actions in terms of resource costs (capital and operating costs) and travellers' response to levels of service, normative supply models usually include performance functions, at least implicitly. They may also interface with demand and passenger assignment models.

To conclude, it is worth mentioning that there is another kind of transportation supply models which we might call "models of supply behavior" or "market supply models". These are intended to predict the decision-making behavior of those who supply transportation facilities and services (Morlok, 1980). These modelling efforts are of course extremely important for a comprehensive understanding of the global demand-supply equilibrium process, as well as to help a transportation operator to predict the behavior of its competitors. However, this area of research is still in its infancy and is quite different in essence from the other two approaches introduced above; we will not deal with it in this paper.

3. HIERARCHICAL DECISION-MAKING FOR TRANSPORTATION PLANNING AND MANAGEMENT

To complete our conceptual framework, we now present a broad hierarchical picture of the planning and management process in intercity passenger transportation. This will help us to position the models reviewed in the next sections with respect to each other, and within an understandable taxonomy of the different categories of problems. Also, it will help us to identify and qualify opportunities for future research.

Broadly speaking, we may view transportation supply planning and management as a complex decision-making process characterized by the multiplicity of possible decisions, the necessity of taking decisions at different levels, the high interaction between all decisions and their various impacts, and the need to work in a constraining complex environment which has direct and indirect impacts on decision-making. As emphasized by Assad (1980) with regard to the particular case of rail management, decisions of interest vary substantially in scope, time horizon, investment requirements, and the level of decision-making within the organization (transportation company or government agency).

In order to clarify the discussion, following Assad and other transportation analysts (Soumis, 1979a; Wong, 1984; Bodin et al., 1983), we will identify three levels of decisions : strategic, tactical and operational.

At the highest and most aggregate level, i.e. the strategic level, decision-making is applied to the definition of a supply policy for the organization, as well as to resource acquisition and major investment allocations over long time horizons. Decision-making problems at this top level of the organization have system-wide long-lasting impacts. They deal with : network design and improvement, implementation of possible new service links, terminal capacity planning and location, fleet acquisition, etc. This system definition and analysis typically involves major capital

investments for new transportation facilities or services, and it must take into consideration the state of the transportation market, demographic trends, the prediction of transportation demand, the position of competive modes and companies, etc. It must also consider, at least to some extent, the economic context (capital cost, inflation rate, cost of labour and of energy, ...), the governmental context (transportation policies, support to some mode in particular, ...) and the financial status of the organization.

Tactical decisions, at a lower level, concern questions which are raised regarding planning for the allocation of material resources of the company (or government agency in the case of certain elements of transportation infrastructure) in order to improve its performance, efficiency or productivity. These decisions have medium-term planning horizons and deal mainly with the efficient use of existing resources rather than the acquisition of major new ones. At this level of tactical decision-making, the company addresses problems such as frequency choice for each service considered, broad routing and scheduling of vehicles together with vehicle fleet sizing, maintenance planning and definition of tariffs (if any choice is possible), etc. Of course, tactical decisions must also take into consideration the financial capabilities of the company (budget constraints) and all other constraints such as government regulation with regard to, for instance, authorized variations in service levels and fares.

Finally, at the most disaggregated and lowest level of decision-making, i.e. the operational level, the company has to solve its very short-term problems and organize in detail its day-to-day activities taking into consideration the daily variations of transportation demand, and all other constraints such as union rules, detailed maintenance requirements, etc. Detailed routing and/or scheduling of vehicles and crews, and the

production of timetables for travellers are examples of such very short-term decision problems, while real-time traffic control on a network or at a particular node is an example of operational issues at the lowest level.

The objective of the above three-level classification is not to fix all kinds of transportation planning and management decision-making problems within a specific slot. In fact, a problem such as the determination or evaluation of a service frequency plan could be classified as a strategic issue or a tactical issue, and at the same time, it is also closely related to crew scheduling issues at the operational level. In fact, one could define as many planning/management phases as there are different levels of decision-making problems, depending on the size of the organization, the type of services it offers and its understanding of the planning/management process. For instance, the Israel National Bus Carrier, which offers urban, regional and interurban services, considers five major phases (Ceder and Ponen, 1980) : planning bus trips; planning bus routes; setting time-tables; scheduling buses to trips; and driver assignment. The association of each of these five steps with one particular level in our classification is of course not important.

What is important however is to understand that transportation planning and management covers the full hierarchy of strategic, tactical and operational decision-making situations which involve different problems differentiated in scope, level of detail, time horizon, financial costs, and level of decision-making within the organization.

It is also important to note that predictive and normative supply models as defined in the previous section are relevant to all levels of the planning and management process. However, it may be noted that such models are usually not well-suited for dealing with the risk and uncertainties inherent in some strategic decision-making situations (this idea is borrowed in part from Wong, 1984).

These supply models are more attractive for situations where one is concerned with the combinatorial complexities and interaction effects that arise in well-defined tactical and operational situations where a variety of different decisions and network-wide impacts are being considered simultaneously, so that the selection of supply actions and the detailed prediction of their impacts become a major issue. In fact, normative models ("what should be done in order to...") seem to be best suited to tactical or operational decision-making situations to generate potentially optimal decisions, especially if they include some sort of heuristic process and if they are augmented by predictive ("what if") types of models aimed at addressing underlying impacts. On the other hand, predictive supply models seem to be good tools to screen several potential tactical or operational actions, with normative models as a subsequent tool for improving the design of the most attractive action plan.

As mentioned above, strategic decision-making situations do not so readily lend themselves to the use of normative and predictive supply models. This is particularly true when dealing with a single action plan which may be regarded from a somewhat aggregated point of view. In the case of such situations, as mentioned by Wong (op. cit.), other planning tools such as multi-attribute theory or cost-benefit analysis are more helpful. However, normative and predictive supply models using mathematical programming techniques, or other systematic quantitative devices such as heuristics and simulation, can also be useful at strategic levels of decision-making in which a variety of different investment decisions are being considered.

4. PREDICTIVE SUPPLY MODELS

In the field of intercity passenger transportation, there are relatively few models concerned with the prediction of the impacts of proposed supply actions on the performance of transportation systems, except in the airline context and, to a less extent, in rail planning.

4.1 Air transportation

Various models for the assignment of passengers to airline flight schedules have been proposed in the literature. These models address the following problem : given a daily flight schedule, and information recording the demand distribution by time of day for each origin-destination pair, predict the assignment of passengers to flights. Models which address this problem enable planners and managers to choose flight schedules knowing the likely effect on customers and aircraft occupancy rates. Soumis (1979a) and Soumis et al. (1981) give a survey of these passenger assignment models which usually make use of two factors to determine the passenger's choice of route, namely the attractiveness and availability of alternative routes. The attractiveness factor of a route is a function of the time difference between the passenger's desired departure time and the scheduled departure time of the route, the time duration of the route (number of stops and/or connections), the type of plane, prices, the image of the company, etc. The availability factor of a route is dependent on the aircraft capacity and demand. Most models incorporate the availability factor into the attractiveness factor since the problem is very difficult to solve when aircraft capacities are introduced as explicit constraints.

The most widely used models[1] of this sort are heuristic. Sometimes, the approach is sequential as in Koyama and Yasuda (1974); each flight is

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[1] This overview of the air transportation passenger assignment problem is borrowed in part from the above mentioned paper by Soumis et al. (1981).

filled sequentially and the overflow of passengers is assigned to other flights; see also the model of Elias (1985) which is particularly interesting with regard to the way it deals with route attractiveness. Other heuristic models (for instance Malik, 1976) assign passengers proportionally to flights. For some other heuristic models (Kingsley, 1968), the availability factor is incorporated through a measure of the attractiveness of different aircraft sizes. Air Canada has developed such a model (Gagnon, 1967).

A second important category of models assigning passengers to a flight schedule makes use of mathematical programming methods, with the availability factor appearing as a group of explicit constraints. Several of these models have been developed in research centers, and many of these are integrated into larger normative supply models to determine optimal frequency plans (Agin, 1972; Agin and Cullen, 1974; Daigle, 1976; Scarbrough, 1977; Swan, 1972). In these models and some others (which for instance take advantage of the fact that several origin-destination pairs are serviced by only certain routes; see Currie, Dickey and Price, 1975), passenger assignment is expressed as a large-scale linear programming problem where the objective is to maximize the satisfaction of passengers, i.e. the performance of the system from the users' point of view. Note that in spite of its simple network structure, this kind of problem is difficult to solve.

These linear formulations also have a tendency to generate extreme solutions where some aircraft are used almost to their limit while others are empty. To obviate this drawback and obtain more balanced and realistic solutions, Soumis et al. (1981) proposed a non-linear programming model called MAPUM to solve the passenger assignment problem; this model, which uses the concept of "passenger overload" to integrate the capacity constraints into the objective function, produces "system optimal" solutions in a small amount of computer time. Like certain other predictive models,

it can be used in a man-machine process to evaluate and modify schedules. Also, it can be integrated into a normative supply model to automatically generate schedules (see section 5.2.1).

Another model of Soumis (1979b) uses a "user optimization" approach to determine passenger assignments to flights and takes account of the variability of demand as a function of service levels. The model is made up of a set of non-linear equations which is solved using the Gauss-Siedel method.

Simulation is another method which has proved to be useful for the evaluation of flight schedules. Using historical data, demand for each service can be generated randomly. An example of a simulation model for air transportation is given by Lauchli (1976).

Thus, it appears that the process of passenger assignment to flight schedules has been the subject of extensive research during the last twenty years. To complete our review, the interested reader should consult the list of published papers mentioned by Etschmaier and Mathaisel (1985); note that, as indicated by these two authors, most of the more recent work which is actually applied by airlines is not in the public domain.

The paper by Etschmaier and Mathaisel is interesting also as it points out other important considerations for the evaluation of a flight schedule, i.e. criteria other than an evaluation of passenger assignment among available flights. These two authors identify four other factors that should be considered explicitly and they mention some research contributions concerning each of them. These factors are : evaluation in terms of stability (reliability) of the schedule; evaluation in terms of cockpit and cabin crews (predictive models for such an evaluation are in fact the same as those used for the design of crew schedules - see section 5.2.4); evaluation in terms of ground crews and ground facilities; evaluation in terms of maintenance requirements.

4.2 Rail and bus transportation

As for airlines, simulation models have also been developed for schedule evaluation in passenger rail transportation. An interesting example is the predictive supply model of the S.N.C.F. (Société Nationale des Chemins de Fer Français - French National Rail Company; see Dreuil and Theyssier, 1977), for preparing and evaluating peak-hour train timetables. This model determines train routes (timings and stops) for a suburban line or group of lines, in relation to the flows of passengers seeking trains at a departure station for different destination stations, taking into consideration all imposed train circulation rules and other technical or level-of-service constraints. The train schedule is progressively constructed and simultaneously evaluated by simulation of the behavior of the system (demand queuing and demand-responsive servicing) so as to achieve a uniform spread of passengers among trains and reduce the required rolling stock to a minimum.

The same approach has been applied by the same rail company to help in the definition of a network of lines for rapid trains (S.N.C.F., 1979). A simulation model is used for the construction and evaluation of operating programs (train schedules and occupancy factors) together with the determination of the required vehicle fleet and related measures of economic performance. For a given transportation demand broken down by day, period of the day and service class, the model generates queues which produce train movements while taking into account operating constraints.

Another very interesting model, based on a concept of utility quite similar to the above mentioned attractiveness factor (see section 4.1), has been proposed to solve the passenger assignment problem for the evaluation of train schedules (Aurignac and Benattar, 1982). Given observed passenger flows for each period of a day on an origin-destination pair with a given train schedule, the model determines the theoretical demand distribution as a function of time, i.e. the percentage of travellers who desire to leave

their origin during each interval of the day (for instance every 15 minutes). This theoretical distribution which reflects the real demand is of course quite different from the observed distribution since the latter represents the adaptation of travellers to the actual schedule. To obtain the theoretical distribution, a utility (attractiveness) measure is associated with each train for each category of travellers (a category is defined by a desired departure time) so that a choice probability distribution can be associated with every train for each customer category. Given the theoretical distribution of demand for transportation, a train schedule may be chosen which best fits this distribution. Also, given this theoretical distribution and the level of demand, one may predict the number of passengers in each train of a new schedule, and thus determine train capacities which best fit the demand.

To conclude this section, it is relevant to mention other modelling efforts dealing with the equilibrium between service supply and demand. Equilibrium models developed by Turnquist et al. (1981) and Tatvitie and Hasan (1980) are good examples in spite of the fact that they were specifically developed for transit corridors, i.e. for transportation systems quite different from the intercity case. However, interested readers may find in these studies a few good ideas which could be transposed to intercity transportation, in particular to intercity bus transportation. Those two papers address the strategic level (and the tactical level, at least to some extent) of decision-making.

Turnquist et al. present an analytic tool to guide management in the search for, and evaluation of, operating strategies which meet transit service objectives on single routes or in transit corridors. The model system includes, as basic components, models of supply, demand, costs and performance. Decision variables include bus fares and headway changes, route extensions, new routes, etc. The supply model relates basic perform-

ance measures (travel times, wait and transfer times, access and egress times, ...) to service specification parameters (route location and length, number and location of stops, frequency of service, ...) and to ridership. The demand side of the model system can accept O-D tables or cruder estimates of demand based on less detailed data. The equilibration procedure involves the application of incremental demand techniques to "pivot" on existing ridership and service levels so as to derive new ridership estimates; thus, it is not a very sophisticated approach in comparison with urban multimodal equilibrium techniques; however, at a strategic level, this may prove to be a satisfying methodology.

The equilibrium model of Talvitie and Hasan is more sophisticated from an analytical point of view. It is made up of a set of disaggregate transportation system performance equations and a set of disaggregate travel demand equations. The equilibration of these two sets of equations is formulated as a problem of computing the fixed point of a mapping. The model has been applied to the analysis of work trip mode choice in a radial transportation corridor in the San Francisco Bay Area where bus services and BART services are available. Policy options include bus line and bus stop spacings, bus and BART headways and fares, location of BART stations, residential and employment density distributions, parking costs, etc.

4.3 Research opportunities

Except for airlines, we identified few predictive supply models which attempt to evaluate the impacts of proposed supply actions on users and/or on resources consumed by suppliers. Most existing models are concerned with the assignment of travellers to transportation services, in particular to transportation schedules represented by a space-time network; the central issue is the proper modelling of the behavior of travellers confronted with various alternative routes characterized at each time of the day by different attractiveness and availability (capacity).

In our view, this is effectively the most important direction of research and there is room for much improvement in this area. In other words, we think that, whatever the mode (air, rail or bus), a major research opportunity lies in the development of new predictive models of passenger flows on intercity networks which realistically reflect the effects of changes in service design and prices. This is particularly true in the context of deregulation and increased competition which gives transportation companies new freedom in pricing and service design. A basic classification of approaches can be proposed according to three factors : (i) the type and number of transportation companies considered, (ii) the distinction between fixed demand vs. variable demand, (iii) the distinction between "system optimization" and "user optimization". With regard to the first factor, one may consider the case of a single company model, a single mode/multicompany model, and a multimode/multicompany model. The two other factors are relatively self-explanatory. Also, another important item is the way one deals with capacity limitations.

The airline model of Soumis et al. (1981), like some other similar models, represents a perfect example of a single company model using a "system optimization" approach, with fixed demand. This productive direction of work should now be followed by further research to more realistically model the demand side of the system and its interaction with supply. It should also be applied to other modes of transportation.

First, one should allow some degree of variability of the demand level as a function of the services supplied and prices offered. This is of great importance as there may be considerable changes in trip-making behavior when companies have the possibility of drastically modifying their supply policies. The model of Soumis (1979b), like some others, has already dealt with the relation between demand and service levels, but much yet

remains to be done in this area. Additional research should also address the relation between demand and prices.

A second improvement in this field would be to look at a "user optimum" assignment approach as opposed to the assignment resulting from a "system optimization" approach. Although it is not sure that the former approach would give much better results, research in this direction would give rise to a passenger assignment which would be more theoretically sound since it would result from a more realistic representation of the behavioral decision process of travellers. The difficulty will be to establish an efficient solution technique. Note that, from a theoretical point of view, the "user optimization" approach has already been investigated by some authors (see Soumis, 1979b); however, it remains to be further exploited and experimented in order to best fit customer behavior.

A third direction for research relates to the way one deals with link capacity limitations determining congestion effects. These effects, which are particularly important in the airline context and quite different from those appearing in road transportation[1], are usually taken into consideration in two ways : either through explicit capacity constraints, which make the problem very difficult to solve, or through incorporation of the availability factor into the attractiveness factor. The model of Soumis et al. (1981) takes a different approach by incorporating an availability factor based on the concept of passenger overload into the objective function. As discussed previously, this is an improvement which should be investigated further by other modelling efforts. In addition, research

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[1] In road transportation, especially urban road transportation, congestion is characterized by a link performance (volume-delay) function which reflects increasing travel time when volume increases. In intercity transportation (except by car), link congestion arises when available vehicle capacity is inferior to demand volume and results in the rejection of some passengers; those accepted are however, broadly speaking, not affected by congestion since link travel time is unchanged.

should be devoted to a more detailed representation of route availability; for instance, the aircraft capacity should be broken down by service class and one should take account of booking policies.

With regard to congestion, there is another subject of research which does not seem to have been intensively investigated. This fourth subject, which again is mainly important for air transportation, concerns the analysis of congestion effects at terminals on the performance of the whole transportation system. Network-wide impacts of delays at terminals, due to both airside and landside capacity limitations, should be integrated as a reliability factor into passenger assignment models. Possible approaches may be found in Etschmaier and Rothstein (1973) and Wilson (1977).

A fifth research subject would be to integrate some representation of competing companies of the same mode, thus producing a single mode/multicompany model. A passenger assignment model dealing with various companies servicing the same markets or some parts of those markets would be of more realistic and useful to the company when testing its own strategies in the face of those deployed by its competitors, as well as testing possible new strategies by these competitors.

The last step would be to take into consideration the other modes of transport as well, at least on those market segments where there is effective modal competition. We have not identified any research activity towards the development of such a true multimode/multicompany intercity transportation model for predicting the assignment of passenger flows. This is unfortunate since such a model would be of great value to every company taken individually, and also from a global point of view since deregulation opens up a great range of freedom for supply actions to all modes and companies. Note that the lack of research in this direction is certainly due to the ancitipated high complexity of the problem formulation that would emerge, but also to the scarcity of appropriate data.

It is worth mentioning here another research direction represented by "transportation market games" allowing the simulation and experimentation of transport situations such as those encountered in practice but in a game environment incorporating transportation demand and supply models. The JET-SET system (Lardinois, 1985a, b) is such a computerized multimodal/multicompany transportation game system where participants play the role of planners or managers of intercity transportation companies in a simulated market environment, with a "game master" playing the role of a government agency capable of influencing the evolution of the economic and regulatory context. JET-SET incorporates transportation models for determination of the intercity level of demand and route choice as a function of service levels and fares supplied by all companies; car is an available mode with unlimited capacity. The passenger assignment model assigns passenger flows to each route taking into account their respective attractiveness and availability; passengers in excess on some routes due to a lack of capacity on some segments (arcs) of those routes are reassigned to other best attractive routes until everybody is assigned a route or travel by car. Another computer game of this sort has been set up at M.I.T. for air transportation (Elias, 1979).

Our list of main research opportunities would not be complete without pointing out the need for research to integrate stochasticity considerations into predictive supply models. Such considerations have already been incorporated into some models, like the one of Soumis et al. (1981), with regard to the variability of demand and resulting available capacity. Stochasticity should also be the focus of research on, as mentioned above, congestion effects at terminals which create network-wide delays.

5. NORMATIVE SUPPLY MODELS

Normative supply models can be grouped into three categories according to the time horizon and the capital investment requirement that characterize the situation they address. As emphasized in section 2, they usually include some function or procedure to represent the performance of the transportation system considered (from the point of view of the users and/or from the point of view of the suppliers of transportation facilities or services), and many of them are also concerned with the interface with demand models or trip assignment models.

Network design models (first category) have to be interpreted broadly as including all normative models addressing the choice of arcs (highways, railbeds, ...) and nodes (airports, stations, garages, ...) and their respective capacities to include or add to a transportation network. Definition of the infrastructure of transportation networks, that is link choice and capacity planning as well as terminal capacity planning and location, are the main long-term, strategic problems in this category. These network design problems usually address capital investment situations involving both design costs for the arc and/or node capacities and operating costs. Note also that network design decisions often arise in ways that do not involve major capital investment decision-making and the physical construction of transportation facilities (Wong, 1984). For instance, decisions concerning the provision of additional or new services on particular bus routes can be viewed as adding arcs to the service network. However, such service design decisions are more readily reversible and they usually deal with operating problems like those addressed in the following category.

Routing and/or scheduling models (second category) cover shorter run tactical and operational decisons for the allocation and scheduling of

vehicles among various possible routes as well as crew scheduling. This category also includes vehicle fleet sizing problems since the number of vehicles of each type needed to handle the proposed services effectively must be determined together with a consistent routing policy for such vehicles (Bodin et al., 1983). These models are much more concerned with effective planning and management of operations than the previous category which is more concerned with investment costs.

Transportation control systems (third category) deal with problems of regulating and monitoring the behavior of transportation systems in real-time. This includes for instance air traffic control devices.

In the following sub-sections of the paper, we will not try to present an exhaustive review of all the work which has been undertaken in these three categories. Such a review is outside the scope of this paper. Instead, we will try to characterize major current directions of work with reference to the literature, so as to point out opportunities for further research.

5.1 Network design models

Network design models are usually concerned with the modification of transportation infrastructures by adding new links or improving existing ones; such models apply to many transportation modes : highway, urban mass transit, rail, etc. However, they have the longest and richest history in highway planning; the provision of highway capacity was actually the dominant supply issue in transportation for many years (Turnquist, 1985). As mentioned previously, network design models also apply to node choice decision problems, i.e. problems concerning the location and sizing of terminals. Also, broadly interpreted, they can address situations where one is concerned with service choice decisions, and this is true for all modes of transportation.

A review of many formulations of and solution algorithms for the "classical" network design problem is presented in Dantzig et al. (1976), chapter 4. The interested reader should also refer to Transportation Research, Vol. 13B, No. 1, edited by Boyce (1979); the seven papers included in this issue, together with their respective references, provide an excellent review of formal models of transportation network design. A more recent paper by Wong (1984) presents an introduction to and unifying view of synthetizing network design problems, discusses recent advances in algorithmic methods for solving these models, and summarizes computational experience. See also Magnanti and Wong (1984).

A typical example of a transportation network design model which can be applied to intercity transportation situations - intercity railways or freeway networks, for instance - is given by Boyce and Janson (1980). It is formulated as a discrete network design problem with the objective of minimizing total travel expenditure subject to a budget constraint on the total construction cost of link capacity changes; the problem can be solved for a fixed, given trip distribution or for a trip distribution which is a function of fixed zone-to-zone travel costs; this is satisfactory for intercity railway or freeway networks. (Note that Boyce and Janson consider also situations where, as in urban networks or intercity congested highways, link travel costs are variable functions of link flows; such situations are not usual in most intercity transportation networks where congestion effects appear in a different way.[1])

Another good example is the model developed by Hamzawi (1972) for the planning of a new public transportation system in a travel corridor already serviced by other systems. The model comprises a set of relationships that estimate (i) the (new) system travel demand as a function of a

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[1] For intercity passenger transportation networks, congestion effects depend on both vehicle capacity and demand; the concept of availability of alternative routes is used to deal with capacity limitations. See section 4.

given total common carrier traffic and of the quality of services offered by all transportation systems, (ii) the system design characteristics such as departure frequency, headways, speed and vehicle capacity, (iii) the system costs which include both network and node construction and operating costs as well as costs to system users. The objective function to be minimized is the total system cost per passenger-mile travelled which is defined in terms of two basic design variables, namely the travel speed and vehicle capacity; other design variables are obtained in terms of these two basic ones. The resulting non-linear optimization problem is solved using a classical method, i.e. the Newton-Raphson iterative method applied to two simultaneous non-linear equations. In spite of various simplifications which might be considered somewhat unrealistic, this normative supply model, which includes a demand function sensitive to supply, seems to us an interesting modelling effort for planning. It has been applied by Hamzawi to the design and analysis of a STOL (Short Take Off and Landing) air link between Toronto and Montreal.

5.2 Routing and/or scheduling models

Broadly speaking, routing and/or scheduling problems refer to the effective planning and management of vehicle fleets and associated crews upon which all transportation authorities rely in order to supply transportation services (Bodin et al., 1983). Decisions concerning the spatial configuration of vehicle movements are classified as "routing problems". If explicit consideration is given to the times at which various locations are visited, one is faced with a "scheduling problem". In many cases, the spatial and temporal decisions interact heavily and result in "combined routing and scheduling problems". Turnquist (1985) summarizes the objective of this level of analysis by saying that it is to determine a set of routes over which vehicles will operate, to select frequencies of service on these

routes within the limitations of available vehicle fleet resources, to schedule particular vehicles to those services, and to assign crews to the vehicles. Note that this level of analysis is also very much concerned with the related problem of vehicle fleet size and mix determination since the best solution to the latter problem relies upon efficient vehicle routing and scheduling.

Research in this area of transportation planning and management, at the tactical and operational level of decision-making, has been quite intensive but mainly concentrated in transportation sectors other than intercity passenger transportation, such as pick-up and delivery systems for freight distribution, school-bus transportation, urban mass transit, dial-a-ride systems, etc. The air transportation system is a major exception to this since it has been actually the subject of intensive reseach in routing and scheduling of vehicles and crews. It should be emphasized also that most theoretical and methodological advances achieved so far could be applied to other intercity passenger transportation modes, with small modifications. For a comprehensive survey of problems and solution techniques in this vast domain of research, the reader should refer, amongst others, to Bodin et al. (op. cit), Golden (1984), Rousseau (1984) and Laporte and Nobert (1985).

In the remaining part of this section 5.2, we will briefly review major research activities of greatest interest for the intercity passenger transportation industry.

5.2.1 Aircraft routing and scheduling models

This is far the most intensively explored area of research with regard to intercity passenger transportation problems. The central problem may be broadly stated as follows : given the estimated transportation demand for every passenger origin-destination pair, the configuration of

the route network, and aircraft operating characteristics, determine a flight schedule with associated assignments of aircraft which maximizes company profits and, possibly, passenger satisfaction with regard to the quality of service.

During the 1970's (see Soumis et al., 1980), several linear programming models were proposed using decomposition approaches. The most complete formulations were proposed by Agin (1972), Richardson (1976) and Scarbrough (1977) who considered the aircraft routing problem and its interaction with the passenger assignment problem (see section 4). The objective was in general to minimize the difference between the utilization cost of aircraft and the passenger revenues, taking into account passenger satisfaction; capacity limitations were considered through explicit constraints on the average number of passengers transported by each aircraft. Unfortunately, at that time, this approach was not applicable to problems of realistic size because of computer limitations. Chan (1974) proposed more efficient network flow techniques but his algorithm was implemented only in simplified situations. Other more easily solvable variants such as the large-scale linear programming model of Simpson (1977) have been proposed, but their usefulness is limited because of some approximations used.

Since then, it was recognized, as discussed by Etschmaier and Mathaizel (1985), that in order to obtain meaningful schedules it would be necessary to represent airline operations in considerable detail, including the determination of concurrent flows of passengers, cargo, aircraft and flight crews through a complex space-time network, as well as the determination of other related activities such as those arising at airports. Such a degree of realism and comprehensiveness leads however to intractable problems.

As recognized by Etschmaier and Mathaizel (op. cit.), it is acknowledged today that the airline routing and scheduling problem is best solved through a structured iterative planning process in which various parts of the airline participate. This process is made up of two main phases which are referred to as "schedule construction" and "schedule evaluation". The construction phase is used to generate a draft schedule which serves as input to the evaluation phase, itself made up of different evaluations with regard to various factors. Based on these evaluations, a new draft schedule is prepared and so on.

We have already reviewed schedule evaluation models in section 4. For the schedule construction phase, the models mentioned above (Agin, Richardson, Scarbrough, Chan) are first examples. Many others are listed in Etschmaier and Mathaizel (op. cit.); they involve various levels of sophistication, in particular with respect to the endogenous treatment of passenger assignment and its interaction with aircraft routing.

The most productive direction for research, as indicated also by Turnquist (1985), is represented by the schedule construction model of Soumis et al. (1980) which takes into consideration the complex interaction between aircraft routing and passenger assignment. To do this, the usual aircraft capacity constraint is eliminated at the expense of a more complex but more realistic objective function which includes a factor representing the loss of revenue due to exceeding aircraft capacity, in addition to usual factors related to the utilization cost of aircraft and passenger revenues. The solution technique is a heuristic adaptation of the Frank-Wolfe algorithm and solution times remain quite acceptable for large-scale problems. The main limitation of this routing and scheduling model, like all other similar models (at least to our knowledge), is that is uses a "system optimization" approach for passenger assignment instead of a "user

optimization" approach; a solution technique which would prove to be efficient for large-size problems using the latter approach remains to be discovered.

5.2.2 Train and intercity bus routing and scheduling models

With regard to the intercity bus industry, our review of the literature indicates that models which expressly address the vehicle routing and scheduling issue are practically non-existent. Most publications deal with legislative (regulatory) matters and with well-known demand models. However, as we mentioned at the beginning of section 5.2, a large part of the theoretical and methodological work which as been devoted to generic problems of vehicle routing and scheduling (in particular in the area of mass transit scheduling) is relevant for intercity bus tactical and operational planning (see for instance Bodin et al., 1983).

The paper by Ceder and Gonen (1980) represents one of the few important contributions in the area of intercity bus scheduling. This paper describes the planning process of the Israel National Bus Carrier (see section 3) and includes the presentation of a model for the scheduling (assignment) of buses to given timetables. It is made up of two components. The first one is a model for chaining bus trips together in sequential order so that each chain begins at a depot, contains one or more bus routes (determined in a previous phase) alternating with idle time and/or deadheading trips, and ends at the same depot; the objective of this first stage is to minimize fleet requirements (maximize linkages of routes) and minimize deadheading and idle times (maximize bus and driver utilization). The problem is formulated as a zero-one integer programming model which is converted into a large-scale assignment problem. The second component is a simple transportation model, which assign buses from the various bus depots to the bus schedules generated in the first stage. Another paper by Ceder

and Stern (1981) dealing with the bus scheduling problem together with fleet sizing should interest some readers.

In the area of rail passenger transportation, we have identified one mathematical model addressing a scheduling problem. This model (Bourachot, 1985), which is part of a large computerized decision-making support system (see section 6.2), has been designed for the automatic production of the train traffic operations program in a station. The problem is formulated as a quadratic 0-1 minimization problem which is solved using a branch-and-bound algorithm. This algorithm assigns a route to each train, respecting all physical and operation constraints such as the available platform length and the possibilities of simultaneous entry to and exit from the station resulting from the configuration of safety installations. The objective to be optimized includes timetable s.ability (maintaining sufficient headways between trains), train connection facility (allowing connections on the same platform between trains with a large number of transit passengers) and the assignment of trains with similar destinations to the same group of tracks (allowing easy orientation for passengers); the objective function is obtained by weighting these criteria.

5.2.3 Fleet sizing models

A recent review of this class of models, for all passenger and freight transportation sectors, has been carried out by Turnquist (1985) who proposes a basic classification of approaches according to three factors pertaining to the taxonomy of routing and scheduling problems (see Bodin et al., 1983) : (i) type of traffic pattern served, (ii) shipment size, (iii) deterministic vs. stochastic analysis. In the case of intercity passenger transportation, problems occur which may concern all traffic patterns, i.e. one-to-one, one-to-many and many-to-many; the latter case is however the most relevant. Shipment size classification is not a relevant

issue since a single passenger is considered as one shipment. The deterministic vs. stochastic distinction is a much more relevant issue since intercity transportation demand and the associated available capacity must be regarded, at least to some extent, as stochastic variables.

Deterministic formulations of the fleet sizing problem have been studied quite extensively, together with generic routing and scheduling problems. Two typical examples are the works of Fourer et al. (1977) and of Gertsbach and Gurevich (1977). The former paper presents a linear programming model for passenger rail service which was developed to obtain fleet estimates and to analyze the effects of different fleet management strategies in the US Northeast Corridor (Boston-Washington). Given a train schedule along the corridor (city and time of departure and city and time of arrival for each train) for a typical design day service and the associated demand (minimal capacity) for each train, the model determines car fleet requirements which minimize operating costs and capital costs. Fleet management strategies which are modelled allow for different frequencies between city pairs and modification of the trains' length at selected stations.

The paper by Gertsbach and Gurevich presents a general method for solving a routing-scheduling-fleet sizing problem which can be stated as follows : given a vehicle schedule (i.e. a given set of passages to be undertaken, each defined as a 4-tuple : name of departure terminal, name of arrival terminal and departure and arrival times), determine the minimal fleet-size required and the optimal routes for every vehicle. The method supposes that each vehicle can carry out any passage; this implies that there are no capacity constraints.

In the stochastic class of fleet sizing formulations, Turnquist (op. cit.) emphasizes the lack of research on complex systems. We agree with

him, but it is true however that some modelling efforts do integrate some consideration of stochasticity. This is the case for instance of the aircraft routing and scheduling model of Soumis et al. (1980); this model assumes that the daily demand for each origin-destination pair is a random variable, thus leading to the concept of random passenger overload on each flight-leg (a non-stop component of a flight). In other words, the model, whose decision variables are the fleet, the frequency plan and the schedule, is actually an airline routing-scheduling-fleet sizing model which integrates some stochasticity with regard to transportation demand and aircraft available capacity.

5.2.4 Crew scheduling models

The crew scheduling problem has been the subject of intensive research activity during the last fifteen years, mainly in the area of urban transit and air transportation, and to a lesser extent in the area of intercity bus transportation; crew scheduling for rail operations has not given rise to much research work.

As described by Rousseau (1984), this problem of manpower scheduling in transportation systems arises in two main contexts : in the scheduling of vehicle operators and in-vehicle crews, and in the scheduling of manpower to service vehicles, passengers or freight at terminals. Both cases have been studied extensively, with due consideration for all the difficult constraints imposed by union rules, government regulation and company policies.

Another difficulty which characterizes manpower scheduling problems in transportation is that they are closely interrelated to vehicle scheduling problems in such a way that, at least theoretically, both problems should be integrated into one single model and solved concurrently. This is particularly true when crew costs dominate vehicle operating costs such as

in the bus industry. Unfortunately, in nearly all practical settings, vehicles are scheduled prior to and separate from crews.

In order to obtain a comprehensive and detailed understanding of current mathematical techniques for transportation manpower scheduling, the reader should refer to the previously mentioned paper by Rousseau. Note that the approach presented by this author tries to combine the two problems of vehicle and crew scheculing, in spite of the fact that the vehicle schedule is considered fixed in most of his paper. The interested reader should also refer to the previously mentioned special issue of Computers and Operations Research (Bodin et al., 1983).

5.3 Transportation control systems

Problems of regulating and monitoring the behavior of transportation systems (in particular the movements of vehicles) in more or less real time include, for example, highway traffic control systems, the recording of the position of trains on a rail network, air traffic control systems, etc. Such matters, which usually require a mix of "hardware" devices (electronic traffic signals at highway intersections, systems of communication between air traffic controllers and pilots, etc.) and "software" techniques (simulation models of vehicle entrances at a highway intersection, decision process models to control the queueing of aircrafts at airports, etc.), do not really belong to a review of intercity passenger transportation models.

However, it is worth mentioning that some of these transportation control systems do have much to do with the improvement of the reliabitily and carrying capacity of transportation systems. This is particularly true for air traffic control systems which contribute to airport capacity, both airside and landside. In this sense, these systems, including some mathematical models, are part of the supply planning and management tools which

are the subject of this paper. Two typical examples are the models of Price and Rosenshine (1985) and Mangoubi and Mathaisel (1985). The former is a semi-Markov decision process model used to control landing access at an airport. The latter addresses the airport flight-to-gate assignment problem. Another model dealing with the assignment of aircrafts to parking positions at an airport is presented in Hamon (1980); it is an integer linear programming model designed in the most general way possibl in order to allow easy adaptation to different airports.

The interested reader should also refer to Turnquist (1985) who gives an overview of some major topic areas in the field of transportation control systems, in particular with respect to highway safety, traffic signal systems and air traffic control.

5.4 Research opportunities

Network design models at the strategic level of decision-making have been extensively used in North America for highway network planning. With regard to intercity transportation, this is no longer a crucial area of research. Network design models for other transportation modes (rail, air and intercity bus) have also been the subject of some research, but to a much lesser extent. We believe that this state of affairs represents a major research opportunity. New network design models need to be developed to help companies, at the strategic level of planning and to some extent also at the tactical level, in dealing with difficult design choices that involve both design costs (arcs and/or nodes design costs) and operating costs. Service link and terminal capacity planning and location will always be a central issue in intercity transportation, although major potential improvements are expected to come mainly from better operations planning and management.

One important subject of research in network design modelling is to consider travel demand to be variable as opposed to most of the literature

which usually takes the number of trips from origin to destination to be fixed. This is certainly unfortunate in urban transportation, but also in intercity passenger transportation as well : when one considers the implementation of a new transportation system or service between cities, as well as the location of a new terminal, travel demand cannot be regarded as given since it is dependent on travel costs. In other words, as emphasized by Boyce (1979), the transportation network design problem is a higher order equilibrium problem in which network supply, activity location and travel demand must be considered as one interrelated system.

With regard to vehicle routing and/or scheduling problems as well as related crew scheduling and vehicle fleet sizing problems, a lot of work has been devoted to generic formulations and solution techniques including some expressly applied to the intercity transportation situation. In particular, the air mode and, to a lesser extent, the intercity bus mode have attracted researchers' attention. However, due to the importance of greater efficiency in human and material resource utilization for providing transportation services, there is room for much more theoretical and applied research in this field, including air transportation. In a context of budget limitations and increased competition, routing and scheduling techniques for vehicles and crews will continue to assume a greater role in the improvement of tactical and operational decision-making, resulting in substantial savings.

From our point of view, main opportunities for future research are closely related to those identified for the development of better predictive supply models (see section 4.3) : consideration of variable demand, introduction of the "user optimization" approach in large-scale problems, better representation of capacity limitations on the links of the networks, and consideration of network-wide delays due to possible congestion at

major nodes (terminals). In other words, the most important direction of research is towards the development of large scale vehicle routing and scheduling models integrating (i) a sophisticated representation of the performance of transportation services in terms of attractiveness, availability and reliability, (ii) a passenger assignment (route choice) formulation combined with a demand model allowing for some variability in the level of demand. Some degree of stochasticity should also be considered in such models for better representation of real-life situations.

Of course, for both network design models and routing and scheduling models, an important related research area concerns the development of efficient solution techniques to deal with complex mathematical structures. This means that elegant mathematical formulations have to be proposed together with sophisticated algorithms, either exact or heuristics. In particular, for routing and scheduling models, optimization methods made up of set covering techniques and column generation techniques are of primary interest, along with dynamic programming. Heuristics also will continue to be of primary interest when associated with optimization modules. In addition, it is worth mentioning that elegance and sophistication will be more easily achieved if based on an interactive approach, taking advantage of human expertise to help explore the space of possible solutions and integrate real-life specific constraints.

Both types of models should also benefit from more theoretical and experimental research on the estimation and analysis of real transportation operating costs in the context of complex and large networks. This is not a trivial problem since these costs refer to a mix of various fixed and variable costs corresponding to the acquisition and utilization of many material resources and to the working activities of various human resources; moreover the utilization of these resources is in fact shared by different components of the transportation supply system as well as by

different components of the transportation demand. For instance, a rail track between two cities is usually used by different trains of different classes servicing various city pairs, and different demand markets for each city pair. In such a context, what does it mean when, at the level of the network, we speak of an operating cost per train-km, per car-km or per passenger-km? Is it really valid to apply these kinds of unit cost to the complete network when we know that vehicle traffic and passenger flows are not uniformly distributed? Note that the lack of serious research regarding these matters is in part due to the absence of detailed, comprehensive and consistent data.

The last area of research we reviewed briefly in section 5.3 is dealing with transportation control systems. Certainly, this is a major opportunity for excellent theoretical and applied work in the coming years, in particular concerning the control of terminal activities (especially airport operations). The focus point of research is the development of interactive regulating and monitoring systems based on a sophisticated mix of software and hardware technologies.

6. COMPUTERIZED DECISION SUPPORT SYSTEMS

6.1 Introduction

Transportation planning and management is a very complex and dynamic decision-making process characterized by the multiplicity and diversity of problems to be handled, the necessity of taking decisions at various levels of the organization, and the obligation to deal with different time-horizons. These decisions interact with one another and they must take into consideration various constraints imposed by the technological and socio-economic context. Representing this strategic-tactical-operational decision making process in detail along with the enormous quantity of information involved will never be possible within a single formal model.

In addition, predictive and normative supply models such as those reviewed in this paper are well suited for well-defined, closed problems based on some realistic simplifications of real-life situations, but they are badly suited for ill-defined problems characterized by a large degree of uncertainty, difficulty in defining precise objectives or criteria for evaluation, and the impossibility of modelling all real-life constraints without inacceptable simplifications. In such cases, the major difficulty is usually how to deal with a large amount of dispersed information and process it rapidly in order to clarify the situation and test some alternative aggregate plans.

More important, it is now recognized by most model-builders that the real challenge is not only to develop good models and find efficient solution techniques, but also to find ways to implemennt these models and get them accepted by the organization. Like Bodin et al. (1983) and many others, we agree that one of the most significant impediments to user acceptance of computer systems is the user's feeling of loss of control over the underlying physical system. Furthermore, most computerized models are usually not flexible enough to allow for any insertion of human experience or intuition within the solution process. In other words, most models must be qualified as "deterministic" or "closed" systems because they do not allow the user to intervene within the solution process or to adjust the problem formulation during the execution of the computer program.

Due to these factors, the consensus today is that decision-making is best aided through a well organized dynamic planning and management process in which many parts of the organization participate by interacting with a flexible and user-friendly computerized decision support system. This does not mean that models such as those reviewed in this paper are not considered to be useful tools. The opposite is true : included in a larger and more dynamic interactive system for gathering, organizing and processing data,

these models - if properly adapted to the interactive environment - become practical tools for providing more realistic and more user-acceptable solutions which fit better into the complexity of real-life situations. The three main components of such decision support systems are :

- A data base, including internal user-oriented data handling procedures.
- A man-machine environment allowing the user : to enter and modify data; to participate in the definition of the kind of data processing desired, i.e. the model definition required, including constraints and objective function when optimization is involved; to intervene during the running of the computer program in order to modify or accelerate the solution process, introduce additional constraints, or alter some existing constraints or parameters.
- A set of user-oriented algorithms, which can be modified or replaced when better ones are provided by the scientific literature.

The reader should note that this description of a general decision support system (DSS) is only tentative to indicate the main possible functions of such a system. Other structures have been and will be proposed in the literature. The reader should also understand that the scientific community is still far from such an ideal DSS which would combine the latest advances in the construction of sophisticated transportation models and algorithms, in the development of well-structured data bases and related data handling procedures, and in the elaboration of interactive techniques with flexibility and user-friendliness as main objectives.

The remaining part of section 6 presents typical examples of DSS in the field of intercity passenger transportation. These systems still do not greatly emphasize the incorporation of transportation supply models such as those reviewed in this paper, but they offer the possibility of doing so. Presently, they are essentially daba-base systems including automatic

computational procedures to assist the user in repetitive data handling tasks, and interactive procedures to enter, modify and display the data or computational results.

6.2 Examples of decision support systems

The RAILNET and AFAIG systems developped by the École Polytechnique Fédérale de Lausanne, Switzerland, are examples of DSS developed in the field of intercity passenger transportation.

The RAILNET system (actually named RAILNET II) is an interactive graphic computerized system for railway tactical and operational planning, designed to assist railway planners and managers to develop, analyze and evaluate alternatives concerning alignments, fixed installations and operating programs on railway networks (as well as metro and tramway networks) (see Rivier and Tzieropoulos, 1983; Genton and Rivier, 1982; Tzieropoulos, 1984). It is made up of two components : a data base automatically managing the information on the railway system components, and a set of computer programs allowing the definition, modification and extension of any data in conversational mode to analyze the railway system's operation and to provide, in numerical or graphical displays, the results and performance measures of proposed operation alternatives.

The set of computer programs is composed of three main modules. The first one is used to store the initial data in the data base (network topology, track alignment and layout, signalling and rolling stock characteristic, etc.), to modify the data, and to check it using a graphics display. The second module computes the various running diagrams for each train taken individually (travel time, speed, tractive and bracking efforts, etc.). The third module is used to create timetables during a given period of the day, taking into account interactions between trains, control and safety installations. This third module is not completely auto-

matic : the user has to create the timetables himself step by step by inputing each train, its category, departure and arrival times, stops at stations and time margins, taking into account the constraints created by the running of other trains. However, the computer system offers automatic displays and information on conflicts between trains. The user can erase, transfer, or modify the path of each train on the network.

The AFAIG system (Bourachot, 1984) is a similar interactive-graphic DSS to help in designing and analyzing the operation and track layout of passenger railway stations. It allows : the elaboration of alternative operation programs within the station, including the determination of the occupation of every platform line; the study of different alternatives concerning the layout of fixed installations; the examination of the feasibility of new timetables, originally developed on a network basis, for instance with the help of the RAILNET system.

The software structure and function of AFAIG are similar to the RAILNET system. However, there is one major difference. While RAILNET requires that timetable creation be carried out interactively by the user with the help of the computer system to make calculations and to display the state of the network, the AFAIG system offers the possibility of using an automatic procedure to develop the operation programs, i.e. an integrated computerized model for the assignment of a route to each train within the station, using an optimization algorithm (see section 5.2.2).

The increasing importance of DSS is also well illustrated by the Israel National Bus Carrier project which emphasizes the development of an interactive man/computer system to improve the efficiency of its planning process (Ceder and Gonen, 1980). We do not know if this project - which was to possibly incorporate a computerized bus scheduling model such as the one presented in section 5.2.2 - has actually been implemented. Also, it is

worth mentioning that Etschmaier and Mathaizel (1985) in their review of the airline scheduling problem do point out that the tendency today is towards the development of planning support systems where much of the work may be handled by computer, while many of the crucial decisions and choices are made by humans; also, they point out that quantitative models are useful throughout such systems for constructing schedules (normative supply models) and for evaluating them (predictive supply models) according to the criteria of the various departments of the organization. Such considerations reflect the increasing importance that many researchers assign to the development of DSS.

7. DATA REQUIREMENTS

The development and improvement of predictive and normative supply models as well as of computerized decision support systems is impossible without the availability of high-quality, up-to-date, detailed, comprehensive, and consistent data pertaining to all modes of intercity passenger transportation. This requires the existence of a permanent institutional process to gather and organize data and to make it easily available, with due consideration to confidentiality.

It is worth emphasizing also that, even without mathematical models or sophisticated decision support systems, the existence of high-quality data sets is a prerequisite for any planning or analysis effort. Intercity passenger transportation in particular has been the subject of a permanent debate in Canada. Today, this debate has become even more crucial and difficult in the light of the question of deregulation and government policy concerning subsidies. This kind of debate cannot progress if reliable data sets are not available.

In a recent paper, Miller (1985) reviewed the current state of Canadian intercity travel data bases[1] and evaluated their adequacy for transportation demand analysis and policy decision-making. Not surprisingly, he found these data bases to be inadequate for this task, thus joining the group of researchers and other transportation experts who consider that these data bases have proved to be of some value in past analyses but are unsuitable for the type of analysis and modelling work currently required in the complex and dynamic area of transportation. The reader should refer to Miller's paper for a discussion of key attributes of a good data base; they include comprehensiveness, consistency and spatial disaggregation.

8. CONCLUSION AND GENERAL COMMENTS

In the previous sections, we have reviewed a large number of supply models and related matters in the vast domain of intercity passenger transportation. We have also attempted to characterize these models with regard to normative and predictive approaches, and in relation with the hierarchy of strategic, tactical and operational levels of planning and management. In spite of the size of the domain, we have tried to identify major research directions in the current state-of-the-art and main opportunities for further research. More detailed suggestions for such further research are outside the scope of this paper. We terminated our review with a short presentation of the important research field dealing with computerized decision support systems.

Finally, we wish to conclude this paper with two comments. First, we wish to emphasize the importance of research addressing the development of interactive tools. There is a consensus today among transportation experts

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[1] The four major Canadian data bases which are available were reviewed : a) 1969 CTC on board survey of common carrier passengers in the Windsor-Quebec City corridor, b) 1976 Transport Canada intercity travel data base, c) 1976 Southern Ontario Multimodal Passenger Studies data base, d) 1977-1980 Canadian Travel Survey, conducted by Statistics Canada.

recognizing this; however, we believe it is worth stressing this point again in this discussion of the supply side of transportation in particular. The point is that to gain acceptance for their models by planners and managers in charge of decision-making, researchers have to integrate such models into user-friendly systems. The best models will be rejected if they do not allow some control and decision input from the user. In this sense, interactive systems taking advantage of the most recent advances in computer graphics software and hardware are of primary interest.

Our second comment is concerned with the potential combination of different modelling efforts dealing with different levels of decision-making within a transportation organization. This means that more research should address the development of more comprehensive and model-based hierarchical systems which could be used by various parts of the organization. Researchers are now able to interface certain normative and predictive supply models into more general data based decision support systems, well-structured so as to integrate the three levels of decision-making (strategic, tactical and operational) and flexible enough to be applied to specific real-life situations.

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REFERENCES

AGIN, N. (1972). "An Algorithm for optimal aircraft scheduling". Proceedings of NATO Conference. Sanderfjord, Norway, 317-326.

AGIN, N. and CULLEN, D.E. (1974). "An algorithm for transportation routing and vehicle loading". Mathematica, New York.

ASSAD, A.A. (1980). "Modelling of rail networks : toward a routing/makeup model". Transportation Research B, 14B, 101-114.

AURIGNAC, A. et BENATTAR, M. (1982). "Modèle d'affectation de la demande journalière dans une grille de train". Direction des Études générales et de la recherche, Société nationale des chemins de fer, France. Published in the Revue Générale des Chemins de Fer, April 1982, and also in Les Cahiers Scientifiques de la Revue Transport.

BODIN, L., GOLDEN, B., ASSAD, A. and BALL, M. (1983). "Routing and scheduling of vehicles and crews. The state of the art". Computers and Operations Research 10, 2, 63-211.

BOURACHOT, J. (1985). "Computer aided design for the operation and the track layout of the passenger railway stations : interactive-graphic model AFAIG". Transportation Planning and Technology 9, 271-283.

BOYCE, D.E. (Editor) (1979). "Transportation network design". Transportation Research B 13B, 1.

BOYCE, D.E. and JANSON, B.N. (1980). "A discrete transportation network design problem with combined trip distribution and assignment". Transportation Research B 14B, 147-154.

CEDER, A. and GONEN, D. (1980). "The operational planning process of a bus company". UITP Revue 29, 207-218.

CEDER, A. and STERN, H.I. (1981). "Deficit function bus scheduling with dead-heading trip insertions for fleet size reduction". Transportation Science 15, 4, 338-363.

CHAN, Y.P. (1974). "Route Network Improvement in Air Transportation Schedule Planning". Ph.D. Thesis, Massachusetts Institute of Technology.

CURRIE, G.N., DICKEY, R.W. and PRICE, W.L. (1975). "Forecasting traffic in air transport network", in Management Sciences Applications to Leisure Time Operations, Ladany, S. (ed.)., North-Holland.

DAIGLE, A. (1976). "Modification et implantation d'un modèle linéaire pour une planification à moyen terme d'une flotte d'avions". Publication #48, Centre de recherche sur les transports, Université de Montréal.

DANTZIG, G.B., MAIER, J.F. and LANSDOWNE, Z.F. (1976). "The Application of Decomposition to Transportation Network Analysis". Control Analysis Corporation Tech. Rep. No. DOT-TSC-OST-76-26, Palo Alto, CA.

DREUIL, J. and THEYSSIER, J. (1977). "La détermination des horaires des trains de banlieue en heure de pointe". Direction des études générales et de la recherche, Société nationale des chemins de fer, France. Published in the Revue Générale des Chemins de Fer, May 1977.

ELIAS, A.L. (1979). "The Development of an Operational Game for the U.S. Domestic Airline Industry". Report R78-5, Flight Transportation Laboratory, Massachusetts Institute of Technology.

ELIAS, A.L. (1985). "A Passenger Demand Allocation Model for Airline Simulations". Working paper, Massachusetts Institute of Technology,

ETSCHMAIER, M.M. and ROTHSTEIN, M. (1973). "Estimating the Punctuality Rate Inherent in a Flight Schedule". Technical Report No. 19, Department of Industrial Engineering, University of Pittsburgh.

ETSCHMAIER, M.M. and MATHAISEL, D.F.X. (1985). "Airline scheduling : an overview". Transportation Science 19, 2, 127-138.

FLORIAN, M. and GAUDRY, M. (1980). "A conceptual framework for the supply side in transportation systems". Transportation Research B 14B, 1-8.

FLORIAN, M. and GAUDRY, M. (1981). "Transportation Systems Analysis : Illustration and Extensions of a Conceptual Framework". Publication #227, Centre de recherche sur les transports, Université de Montréal.

FOURER, R., GERTLER, J.B. and SIMKOWITZ, H.J. (1977). "Optimum fleet sizing in the northeast corridor". Transportation Research Record 656, 40-45.

GAGNON, G. (1967). "A model for flowing passengers over airline network". Transportation Science 1, 232-248.

GAUDRY, M. and WILLS, M.J. (1978). "Estimating the functional form of travel demand models". Transportation Research 12, 257-289.

GAUDRY, M. (1984). "Functional form and stochastic specification : current applications to aggregate time-series and cross-sectional travel demand models", in Transportation Planning Models, Florian, M. (ed.), North-Holland, 61-78.

GENTON, D.L. and RIVIER, R.E. (1982). "Outils informatiques d'aide aux planificateurs". Rail International 4.

GERTSBACH, I. and GUREVICH, Y. (1977). "Constructing an optimal fleet for a transportation schedule". Transportation Science 11, 1, 20-36.

GOLDEN, B., ASSAD, A., LEVY, L. and GHEYSENS, F. (1982). "The Fleet Size and Mix Vehicle Routing Problem". Management Science and Statistics Working Paper No. 82-020, University of Maryland at College Park.

GOLDEN, B.L. (1984). "Introduction to and recent advances in vehicle routing methods", in Transportation Planning Models, Florian, M. (ed.), North-Holland, 383-418.

HAMON, J.P. (1980). "Automatic assignment of aircraft to parking positions. Formulation and application to CGD terminal 2". 20th AGIFORS Symposium, 489-523.

HAMSAWI, J.G. (1972). "Intercity Passenger Transport : A System Design Optimization Model". Technical Report 72-1, Faculty of Engineering, Carleton University.

KINGSLEY, D. (1968). "Airline Operation and Planning Model". Paper 505B, McDonald Douglas, Long Beach, CA.

KOYAMA, R. and YASUDA, Y. (1974). "A load distribution and revenue calculation model". 14th AGIFORS Symposium, 405-435.

LAPORTE, G. and NOBERT, Y. (1985). "Exact Algorithms for the Vehicle Routing Problem". Publication G-85-11, GERAD, École des Hautes Études Commerciales. To be published in Surveys on Combinatorial Optimization, Martello, S., Laporte, G., Minoux, M. and Rebeiro, C. (ed.), North-Holland Publishing, 1986.

LARDINOIS, C., CORMIER, M. and ROY, S. (1985a). "JET-SET. Jeu éducatif en transport/Simulation for Education in Transportation. Part 1. Operation and Rules of the Game". Publication 405, Centre de recherche sur les transports, Université de Montréal, (Available in English or French).

LARDINOIS, C., D'AVIGNON, J. and HIROU, C. (1985b). "JET-SET. Jeu éducatif en transport/Simulation for Education in Transportation. Synthesis". Publication #407-A, Centre de recherche sur les transports, Université de Montréal, (available in English or French). Published in French in the Proceedings of the 20th Annual Meeting of the Canadian Transportation Research Forum, Toronto.

LAUCHLI, U. (1976). "Matching transportation capacity to a stochastic transportation demand". 16th AGIFORS Symposium, 83-101.

LERMAN, S.R. (1984). "Recent advances in disaggregate demand modelling", in Transportation Planning Models, Florian, M. (ed.), North-Holland, 3-18.

MAGNANTI, T.L. and WONG, R.T. (1984). "Network design and transportation planning : models and algorithms". Transportation Science 18, 1-55.

MALIK, H.I. (1976). "Airline schedule planning and economic evaluation model". 16th AGIFORS Symposium, 137-160.

MANGOUBI, R.S. and MATHAISEL, D.F.X. (1985). "Optimizing gate assignments at airport terminals". Transportation Science 19, 2, 173-188.

MANHEIM, M.L. (1980). "Understanding supply in transportation systems". Transportation Research A 14A, 119-135.

MILLER, E.J. (1985). "The data base for intercity passenger travel analysis : current state and future prospects". Proceedings of the 20th Annual Meeting of the Canadian Transportation Research Forum, Toronto.

MORLOK, E.K. (1980). "Types of transportation supply functions and their Applications". Transportation Research B 14B, 9-27.

RICE, R.G., MILLER, E.J., STEWART, G.N., RIDOUT, R. and BROWN, M. (1981). "Review and Development of Intercity Passenger Demand Models". Research Report No. 77, Joint Program in Transportation, University of Toronto and York University.

RICHARDSON, R.J. (1976). "An optimization approach to routing aircraft". Transportation Science 10, 52-71.

RIVIER, R.E. and TZIEROPOULOS, P. (1983). "Interactive Graphic Models for Railway Operational Planning". Doc. No. 726/5, Institut des transports et de planification, École Polytechnique Fédérale de Lausanne (Switzerland). To be published by North-Holland in the Proceedings of the course "The Practice of Transportation Planning", organized by the International Center for Transportation Studies, held in Amalfi (Italy).

ROUSSEAU, J.-M. (1984). "Crew scheduling methods in the operation and planning of transportation systems", in Transportation Planning Models, Florian, M. (ed). North-Holland, 439-472.

RUE, R.C. and ROSENSHINE, M. (1985). "The application of semi-Markov processes to queuing of aircraft for landing at an airport". Transportation Science 19, 2, 154-172.

SCARBROUGH, J. (1977). "A Mixed Integer Programming Model for the Scheduling of Aircraft by Time of Day within a Network of Airports". TIMS/ORSA Meeting, San Francisco.

SIMPSON, R.W. (1977). "Advanced Airline Planning Models. A Tool for Developing Regulatory Policy". CTS Report 77-8, Center for Transportation Studies, Massachusetts Institute of Technology.

SOUMIS, F. (1979a). "Planification d'une flotte d'avions". Thèse de Ph.D., Publication #133, Centre de recherche sur les transports, Université de Montréal.

SOUMIS, F. (1979b). "Modèles de comportement des clients du transport aérien", in Comparison of Automatic Control and Operational Research Techniques Applied to Large Systems Analysis and Control, Pelegrin, M. and Delmas, J. (ed.), IFAC/IFORS Symposium, Toulouse, France, 6-8 March. Pergamon Press.

S.N.C.F. (1979). "Modèle de simulation pour la définition d'un réseau de lignes à grande vitesse pour le transport des voyageurs". RK No. 79-381, Direction des études générales et de la recherche, Société nationale des chemins de fer, France.

SOUMIS, F., FERLAND, J.A. and ROUSSEAU, J.-M. (1980). "A model for large-scale aircraft routing and scheduling problems". Transportation Research B 14B, 191-201.

SOUMIS, F., FERLAND, J.A. and ROUSSEAU, J.-M. (1981). "MAPUM : A model for assigning passengers to a flight schedule". Transportation Research A 15A, 155-162.

STOPHER, P.R. and MEYBRUG, A.H. (Editors) (1976). Behavioral Travel-Demand Models, Lexington Books, Mass.

SWAN, W. (1972). "The Complete FA-4 Memo". Technical Memorandum 72-10, Flight Transportation Laboratory, Massachusetts Institute of Technology.

TALVITIE, A. and HASAN, I. (1980). "An equilibrium model for transportation corridors and its application." Transportation Research B 14B, 165,174.

TURNQUIST, M.A., MEYBURG, A.H. and RITCHIE, J.F. (1981). "An Equilibrium Model for Short-Range Transit Planning", presented at the International Symposium on Frontiers in Transportation Equilibrium and Supply Models, Montreal.

TURNQUIST, M.A. (1985). "Research in Transportation System Characteristics and Operations". Resource Paper for Supply Workshop, National Science Foundation Conference on Transportation Research, Evanston, Illinois, March 20-22.

TZIEROPOULOS, P. (1984). "RAILNET II. Aperçu général du modèle". Doc. 726/1, Institut des transports et de planification. École Polytechnique Fédérale de Lausanne (Switzerland).

WILSON, B. (1977). "A rapid computer method of schedule testing for punctuality". AGIFORS 18.

WONG, R.T. (1984). "Introduction and recent advances in network design : models and algorithms", in Transportation Planning Models, Florian, M. (ed.), North-Holland, 187-225.